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How rock mechanical properties affect fault permeability in Neogene mudstone?

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Abstract

We investigate the relationship of permeability of fault developing in Neogene mudstone layer with mechanical properties of the host rock and stress condition (or depth) at the faulting, focusing on the Wakkanai Formation (middle to late Miocene, siliceous mudstone) and the Koetoi Formation (late Miocene to Pliocene, diatomaceous mudstone) at the Horonobe area, northern Hokkaido. Based on the previous studies, including laboratory experiments to measure permeability evolution along a shear zone induced in mudstone specimen. We constructed the model of fault permeability evolution for these Neogene siliceous formations; in the case of Koetoi Formation, where opal A to opal CT transition in diagenesis is not clearly observed, failure envelope is influenced by maximum burial depth, and when fault is created at the depth close to the maximum burial depth, fault becomes compact and the permeability is not high comparing to the host rock. On the other hand, in the case of Wakkanai Fm, pore collapse condition of failure envelope is much larger than the stress condition expected from maximum burial depth because hardening in diagenesis is strong, mainly by opal A to opal CT transition in diagenesis, and therefore faults induced at the depth shallower or similar to the maximum burial depth is dilative and high permeable. This model can be applied to general Neogene siliceous mudstone for assessment of seal properties of mudstone formations.

Keywords: fault permeability; Neogene siliceous mudstone; seal layer; laboratory experiment

1. Introduction

In CO_2 geological sequestration, fault permeability evaluation in a seal layer (e.g. mudstone) is a critical issue. Fault permeability generally depends on several factors such as mechanical and hydraulic properties of host rock or stress condition [1], but how depends is still not clear enough to be applied to

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the fault permeability evaluation. We herein discuss how fault permeability in Neogene mudstone depends on mechanical properties of host rock and stress condition under which the fault develops.

We focus on Neogene siliceous mudstones, Wakkanai Formation (Fm) and Koetoi Fm, observed at the Horonobe area, northern Hokkaido. Siliceous sedimentary rocks similar to those formations are commonly found in Neogene sedimentary basins in the world such as the circum-Pacific region [2] (e.g., Moterey Fm, California). In this paper we first review the relationship between characteristics of fault or shear fracture permeability in mudstone and mechanical properties of the host rock, and also review factors affecting the mechanical properties. We then, following description of Wakkanai and Koetoi Fm mudstone, we show results of laboratory experiments which investigated permeability developments of shear zone induced in these mudstone specimens. Finally we construct a model of fault permeability developed in these mudstone Fms.

2. Fault permeability in mudstone and its mechanical properties

Fault permeability in mudstone depends on mechanical properties of the host rock. In general, dilatant, permeable shear fractures occur in rocks during deformation under low confining pressure and/or in relatively strong rocks, while compacting shear fractures occur during deformation of rocks at high confining pressure and/or during deformation of weak or ductile rocks (Fig.1, [3]).

Several factors affect mechanical properties of Neogene mudstone. One of them is maximum stress that the rock has experienced, which in many cases depends on maximum burial depth (e.g., [4]). When mud yields, failure envelope in Fig. 1 extends to higher normal stress condition (e.g., [5]).

Chemical and/or physical processes such as cementations between grains also affect the mechanical properties. In the case of siliceous mudstone, opal CT to opal A transition of amorphous silica is observed in diagenesis. Boundary between Wakkanai and Koetoi Fms coincides with this transition, and mechanical and transport properties clearly changes across their boundary [6,7].

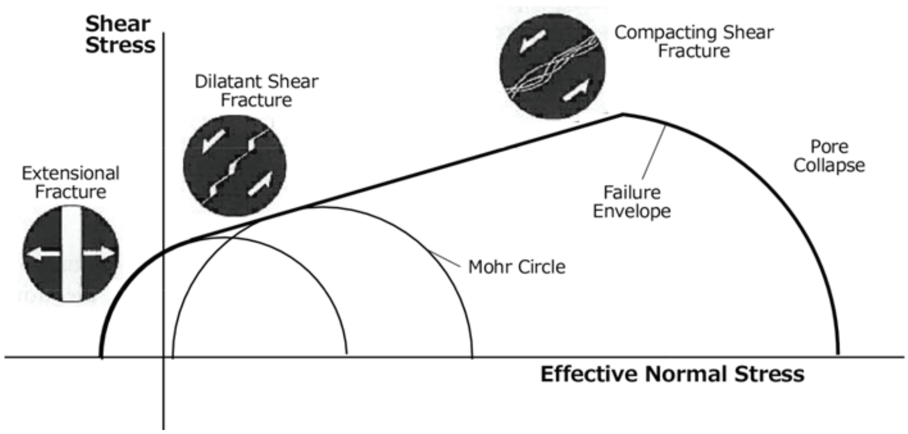

Fig. 1. Mode of fracture formation [3].

3. Geological setting of Horonobe area

The Horonobe region is located on the eastern margin of the Tenpoku sedimentary basin in northern Hokkaido, northern Japan (Fig. 2). The region consists of Neogene sedimentary formations, ranging in thickness from several hundred meters to several kilometers, overlain by Quaternary formations and terrace sediments [6, 8]. The formations have formed a fold-and-thrust belt of northern Hokkaido under EW compressive tectonics. Niizato et al. [9] has revealed that the folding and thrusting began in the Late Pliocene period, resulting in uplifting of the area. Horonobe Underground Research Center of Japan Atomic Energy Agency (JAEA) has conducted detailed geological and hydrological studies in the Horonobe area where major anticlines and faults are developed [10].

The Wakkanai Fm (middle to late Miocene, siliceous mudstone) is cemented more strongly than the overlying the Koetoi Fm (late Miocene to Pliocene, diatomaceous mudstone). Fukusawa [6] suggests that the Koetoi and Wakkanai Fms both consists mainly of diatomaceous mudstone, but that their properties differ from each other because the phase of amorphous silica changes from opal A to opal CT at the boundary between these formations.

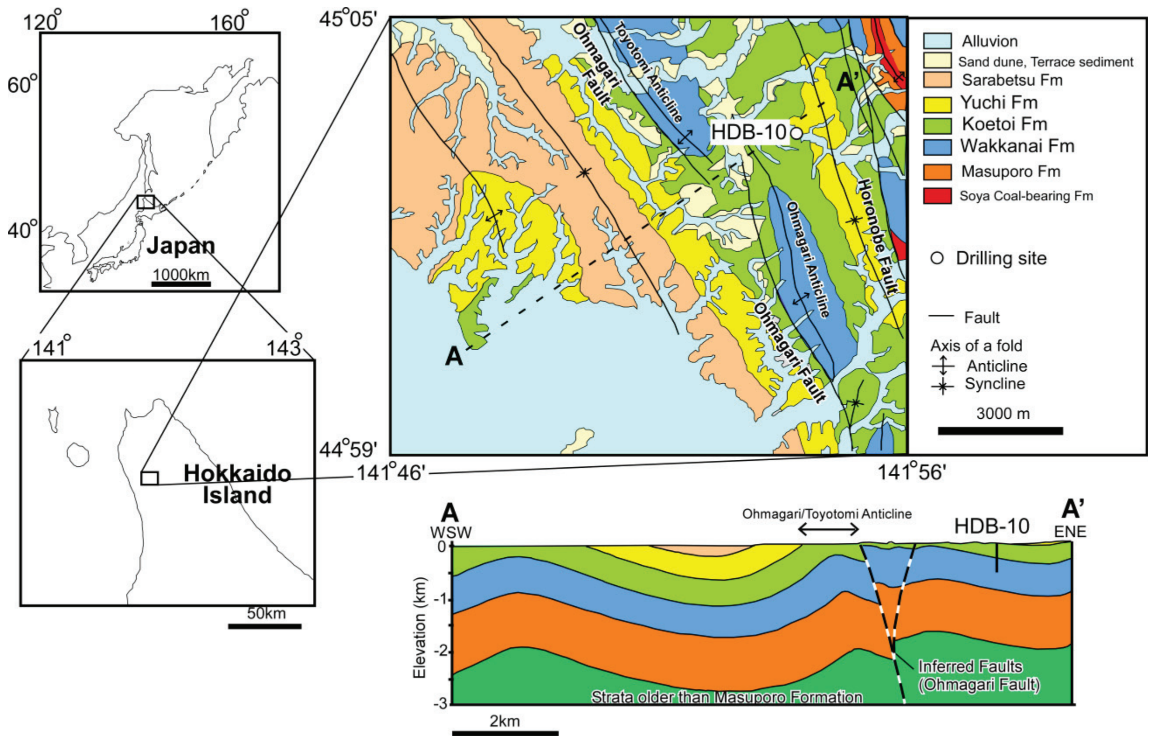

Fig. 2. (a), (b) Location maps (left), (c) a geological map of the study area with a location of drill hole HDB 10 (upper-right) and (d) a geological cross-section (lower-right) along the A-A' line in the geological map (compiled from previous studies, e.g., [10]).

4. Hydraulic features of Wakkanai and Koetoi Formations

Studies in this area including in-situ flow monitorings and observations of drill cores and borehole walls have revealed that, interestingly, Koetoi Fm and Wakkanai Fm show the different relationship between fault/fracture distribution and groundwater flow: the flow paths in Wakkanai Fm seemed to concentrate at several locations where faults/fractures were frequently observed. On the other hand, this tendency was weak in Koetoi Fm [11]. Uehara et al. [12] also showed the difference on effects of faults and fractures on permeability, by comparing results of laboratory permeability measurements with results of in-situ hydraulic conductivity measurements. Ishii et al. [7] showed that this difference on flow properties can be explained by difference on deformation type, i.e., brittle or ductile, and can be characterized by using a brittleness index (BRI) given by laboratory tests, which is the ratio of unconfined compressive strength to effective vertical stress.

In order to understand deeply the relationship between deformation style and the flow properties at the Horonobe area, and to reveal factors controlling the flow properties, it is valuable to operate laboratory experiments to measure permeability evolution during shear deformation for the mudstones. Uehara and Takahashi [13] operated experimental measurements of permeability changes along shear zone induced in mudstones collected from Koetoi and Wakkanai Fm. We describe in detail this study in the next chapter.

5. Laboratory experiments of induced shear zone permeability

5.1. Descriptions of the experiments

Uehara and Takahashi [13] adopted a specimen arrangement similar to experiments of Takahashi [14]. A cylindrical mudstone specimen was put between cylindrical Berea sandstone specimens. The sandstone cylinders have saw-cut plane in order to induce shear zone in the mudstone specimen when axial force is applied. An advantage of this method is that we can see whether flow rate along induced shear zone, or fault, is effectively large comparing to the intact part (Fig. 3). We set confining pressure and average pore pressure as 8.3 and 4.9MPa, respectively, considering conditions at a depth of approximately 5e2 m. Distilled water was We used as a pore fluid and the experiments were operated under room temperature. An axial displacement was applied with a constant velocity, 0.2 m/sec, and permeability of the axial direction was measured by oscillation pore pressure method. The specimens were prepared from three locations of the drilling core of HDB 10 obtained by JAEA; 43.2m, 264.0m, (Koetoi Fm), and 385.0m (Wakkanai Fm) in depth, which are called as Kt43m, Kt264m, and Wk385m, respectively. We show the results of Kt43m and Wk385m in Fig. 4. The location of HDB 10 was shown in Fig. 1.

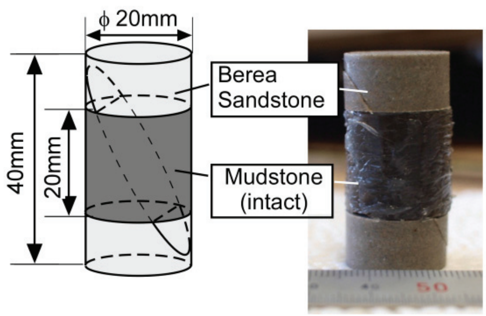

Fig. 3. Specimen used in laboratory experiments of [13].

5.2. Results of the experiments

Main results of [13] are as follows (Fig. 4). (1) After differential stress reaches a peak, it keeps almost constant for Kt43m, while the value decreases drastically for Wk385m. (2) Measured permeability is similar to that before deformation, or intact permeability, for Kt43m, while the permeability increases after deformation in the case of Wk385m. (3) X-ray CT images of induced shear zones indicated that the shear zone of Kt43m is compacted, while that of Wk385m is dilative, which suggested that the shear zone may work as a conduit. Our results in this study can successfully explain why there are differences of observed in-situ shear zone flow properties between Koetoi and Wakkanai Fms may be related to the differences in observed in-situ flow.

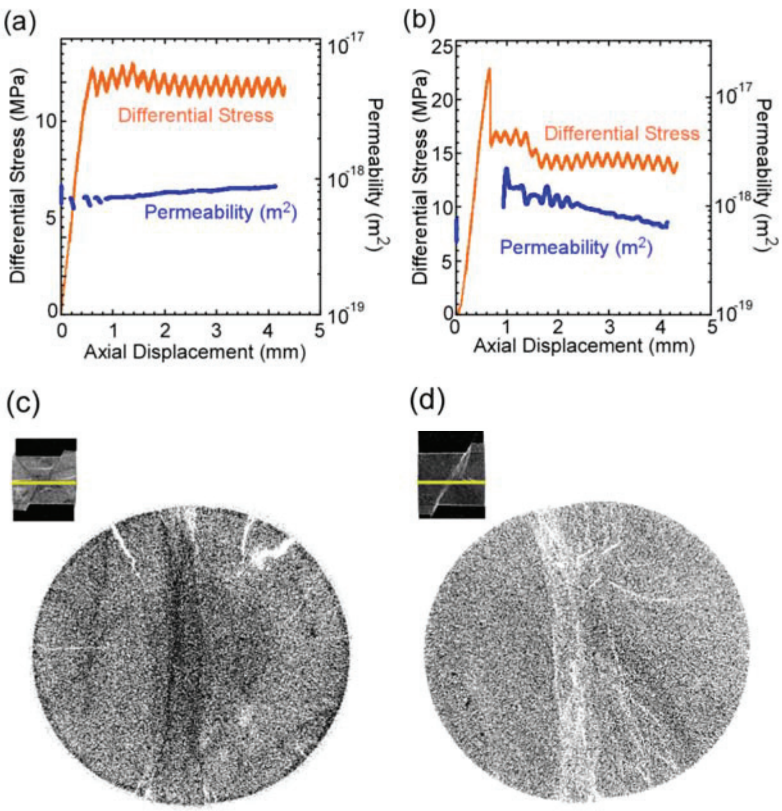

Fig. 4. Laboratory test results [13]. (a),(b) Differential stress and permeability as a function of axial displacement: (a) Koetoi Fm mudstone (Kt43m). (b) Wakkanai Fm mudstone (Wk385m); (c), (d) Cross section of micro focus X-ray CT images: (c) Koetoi Fm. mudstone (Kt43m). (d) Wakkanai Fm mudstone (Wk385m). In general, the lighter color is, the less density is.

6. Fault permeability evolution model for siliceous mudstone formations in Horonobe

6.1. Relationship between failure envelope and permeability of induced shear zone

Based on the results of Uehara and Takahashi [13] and other previous studies, we investigate the relationship between failure envelope and permeability of induced shear zone.

From previous studies [15,16], failure envelopes for Koetoi and Wakkanai Fms can be estimated (Fig. 5). Koetoi Fm mudstone yields under hydrostatic condition when confining stress are approximately 10 MPa (Fig. 5). When we roughly draw in Fig. 5 pore collapse condition of Koetoi Fm mudstone based on this stress condition, the pore collapse condition is close to that under which laboratory experiments of [13] were operated, which is consistent with that compacting shear zone was induced, following the model shown in Fig. 1. On the other hand, in the case of Wakkanai Fm mudstone, yielding under hydrostatic condition has not been reported under stress conditions close to the experimental condition of [13], and therefore shear zone was induced under stress condition far from pore collapse condition, which also follows the model shown in Fig. 1.

6.2. Factors affecting failure envelopes of Koetoi and Wakkanai Fm mudstone

Here we try to estimate maximum burial depth of these Fms, and investigate its relationship to the failure envelopes of these mudstones.

Based on the assumption from the model of [8] that the diagenesis had finished before the formation of the fold-and-thrust belt of northern Hokkaido, the boundary between Koetoi and Wakkanai Fms can be a useful reference because the boundary coincides with opal A to opal CT transition in diagenesis. This phase transition mainly depends on temperature, and by assuming a typical thermal gradient, the depth for this phase transition is estimated to be approximately 1e3 m for siliceous mudstones in Japan [17]. In the case of Kt43m and Wk385m, the distances between the sampling location and the boundary plane between Koetoi and Wakkanai Fms are 189 and 72 m, respectively, which are calculated with an average dip of Fms, 38 deg. at HDB 10, and the depth of the boundary, 290 m. Maximum burial depth of Kt43m and Wk385m, therefore, are estimated to be approximately 8.1e2 and 1.07e3 m, respectively.

These depths corresponds to approximately 7.9 and 10.5 MPa, respectively, given a rock density of 2 g/cm3 and hydrostatic pore pressure. In the case of Kt43m, the estimated "maximum stress ever applied" is close to yielding stress under hydrostatic condition for Koetoi Fm mudstone reported by [16] (approximately 10 MPa, Fig. 5). This result supports that the pore collapse condition of Koetoi Fm mudstone roughly can be explained by maximum burial depth. The reason why this estimated value is a few MPa less than the yielding stress reported by [16] can partially be because of hardening caused by some diagenesis processes. In the case of Wk385m, on the other hand, the estimated maximum stress cannot explain the yielding stress. This probably means effect on hardening of diagenesis processes including opal A to opal CT transition is much larger than Koetoi Fm mudstone.

6.3. Fault permeability evolution model for Koetoi and Wakkanai Fm mudstone

Based on the above discussion, the following model of fault permeability evolution for Koetoi and Wakkanai Fm mudstone can be constructed.

In the case of Koetoi Fm, failure envelope almost depends on maximum burial depth. When fault is created at the depth close to the maximum burial depth during uplifting process at folding and thrusting, fault becomes compact and the permeability is not high comparing to the host rock. In the case of Kt43m, estimated maximum burial depth and depth corresponding to stress condition of the experiment, are approximately 5e2 m and 8.1e2 m, respectively, and in this case, compacting fault is induced. When fault is created under less stress condition, the fault permeability could be higher than host rock and be a effective flow path. Comparison laboratory permeability measurement results with in-situ hydraulic conductivity measurements at HDB 10 borehole suggested that the hydraulic conductivity values from in-situ measurements at the depth shallower than 100 m tends to be larger than values estimated based on laboratory experiments with host rock specimen[12], which possibly reflects that faults or fractures developing at shallower depth can be a dilative and an effective flow path.

In the case of Wakkanai Fm, pore collapse condition is probably much larger than that expected from maximum burial depth. Comparing with Koetoi Fm, the effect on hardening is strong, mainly by opal A to opal CT transition in diagenesis, and therefore faults induced at the depth shallower or similar to the maximum burial depth can be dilative and high permeable.

This model can be applied to general Neogene siliceous mudstone for assessment of seal properties of mudstone formations, by using with information of geological setting and/or geophysical explorations

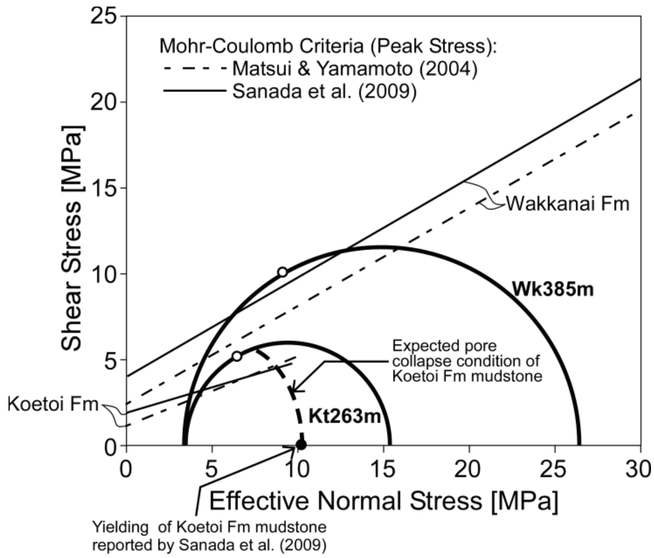

Fig. 5. Mohr circles and stress conditions (open circles) at the peak axial stress, and Mohr-Coulomb criteria for peak stresses of Koetoi and Wakkanai Fm mudstone based on Matsui and Yamamoto (2004) and Sanada et al. (2009). The stress condition were estimated on the assumption that shear stresses at the mudstone and pre-cut surfaces of sandstone are the same. Sanada et al. (2009) also reported that Koetoi Fm mudstone yields under hydrostatic stress condition ($\sigma1 = \sigma2 = \sigma3$) when a confining pressure is approx. 10 MPa (closed circle), which might reflect pore collapse.

Acknowledgements

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